Bio-Inspired Odor Source Localization

SOAR2 Review

12-15 JULY 2011

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AFRL/RWGIA

Air Force Research Laboratory

Integrity □ Service □ Excellence

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUL 2011	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Bio-Inspired Odor Source Localization	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM202973. BioMav SOAR 2. Held at Chilworth Manor, United Kingdom on July 12-15, 2011. Supporting documents are attached to the report as separate files (WMV; AVI)., The original document contains color images.

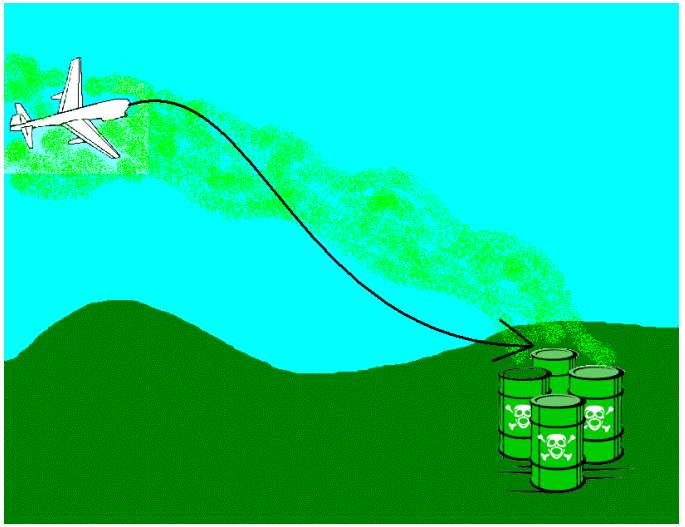
14. ABSTRACT

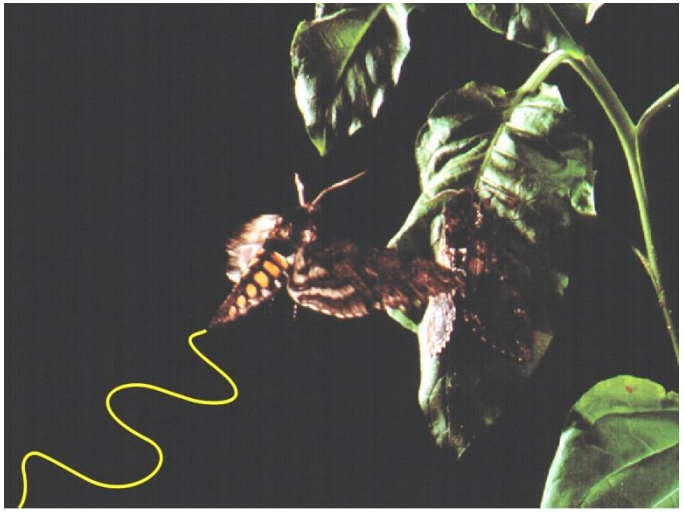
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**34**	

Why study odor tracking?

- Engineer odor tracking systems
  - Gas leaks
  - Hazardous waste
  - Explosive devices
  - Biological principles
- Understand biological principles
  - Mate/food finding
  - Pest population control
  - Engineered odor tracking systems





Manduca sexta

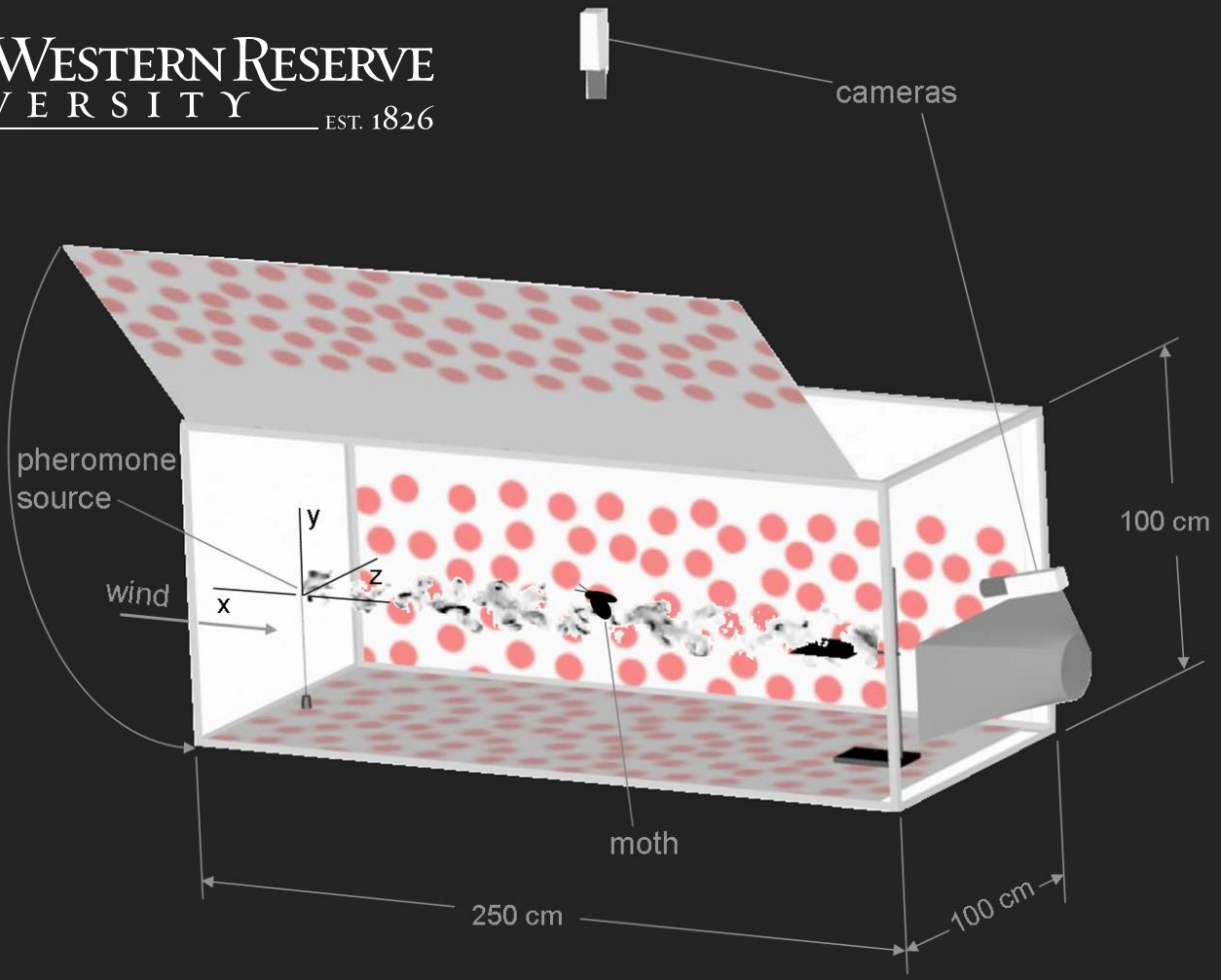
Odor tracking overview

- Odor plume properties
  - carried by wind
  - invisible
  - turbulent
  - artificial: hazardous waste, explosives
  - natural: pheromone, food

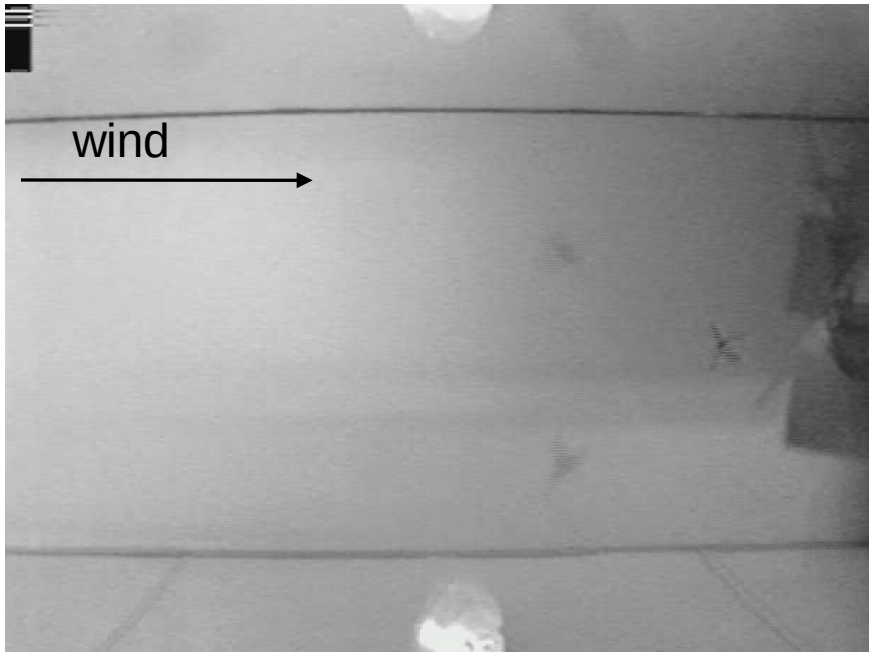
- Tracking agents
  - engineered: UAVs, UGVs, AUVs
  - natural: moths, cockroaches, fish

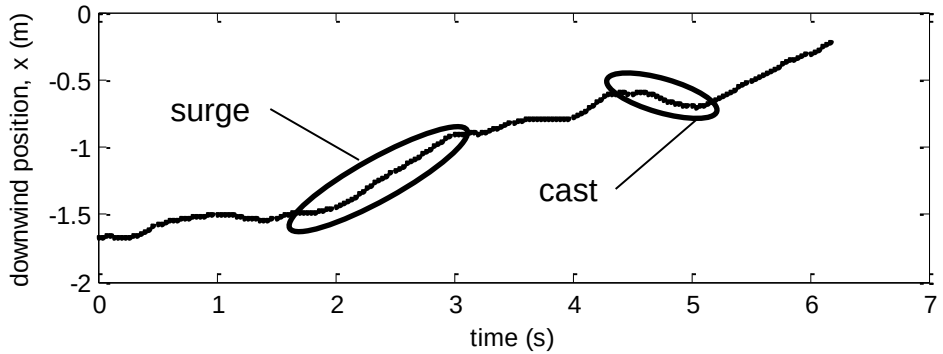
Moth Odor Tracking Studies

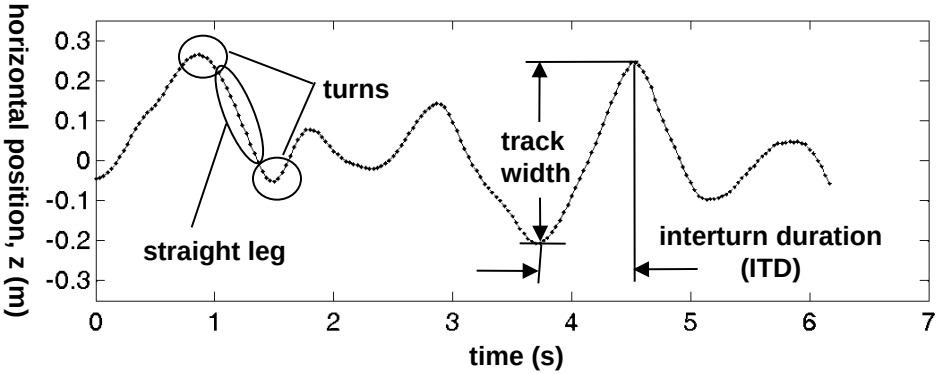
CASE WESTERN RESERVE UNIVERSITY EST. 1826



Traditional 2D Analysis

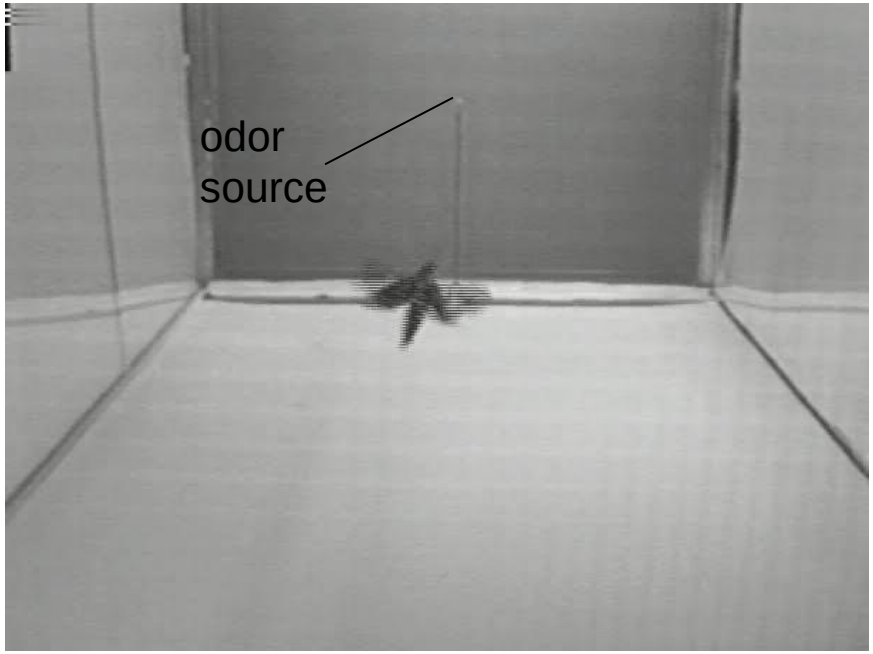




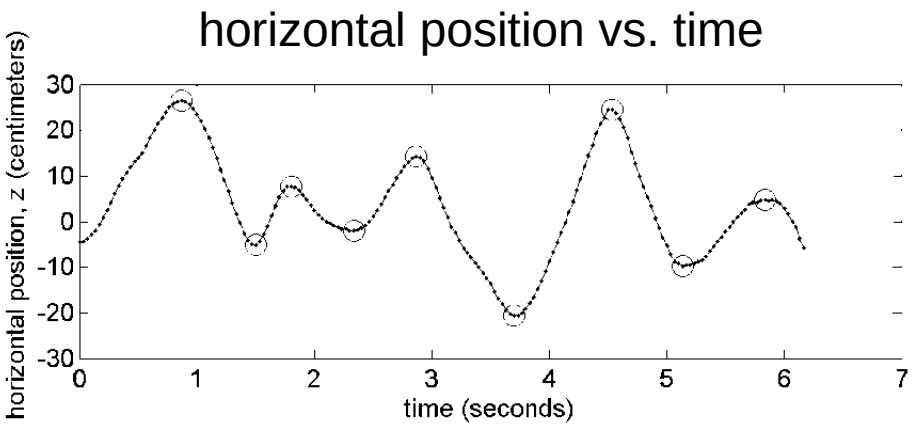


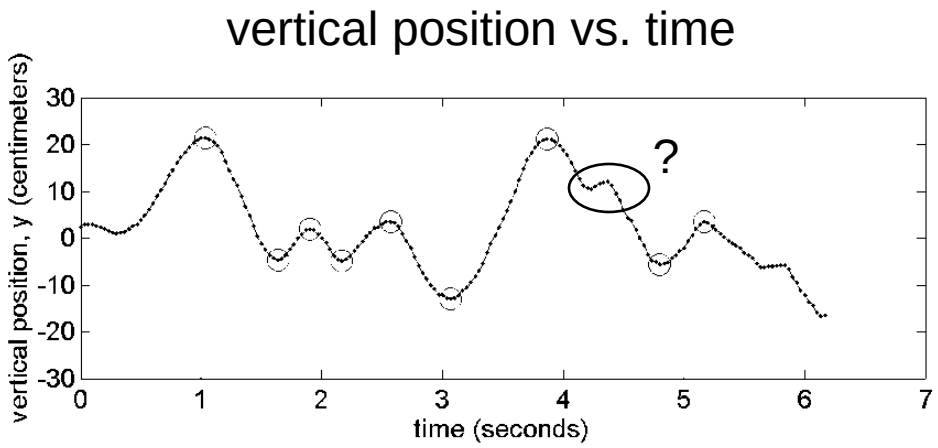
- Odor-modulated anemotaxis
  - Move upwind (surge) when odor detected, move downwind (cast) when odor lost
  - Combination of straight legs and turns (zigzagging)
  - Turning controlled by a timing mechanism (interturn duration of 580 ms)
- Odor plume altitude is maintained

3D Analysis



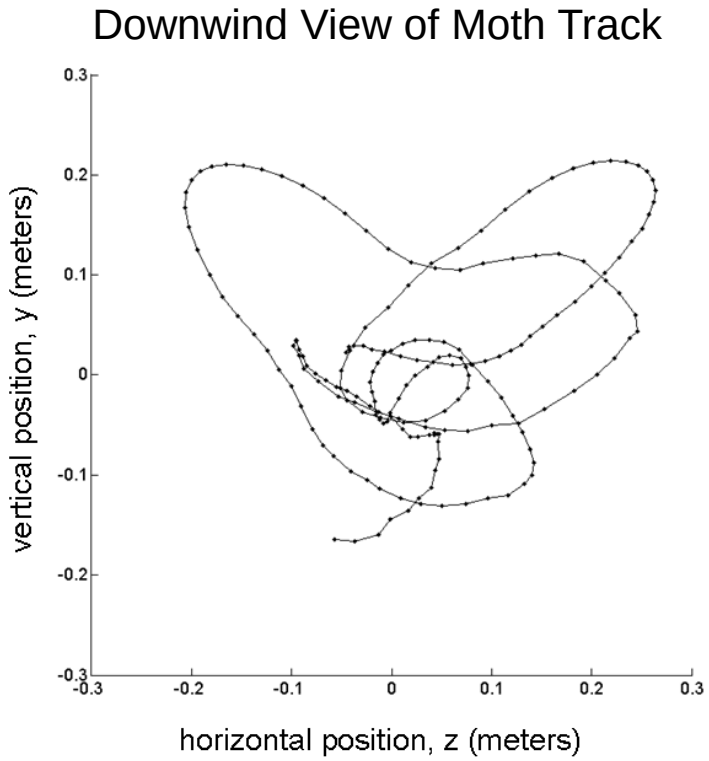
- Counter-turns vertically with average ITD of 550 ms (90-95% of horizontal ITD)
- Vertical track width 75% of horizontal track width
- Temporal relationship between vertical and horizontal turns is unpredictable
- Turns are ambiguous (in both y and z)

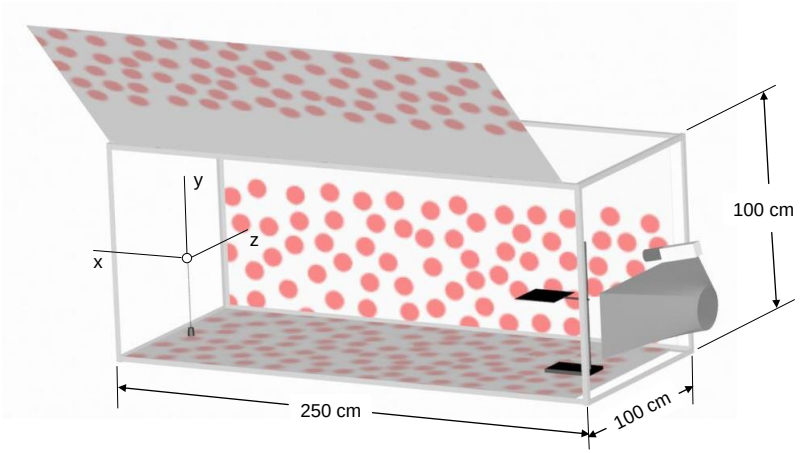


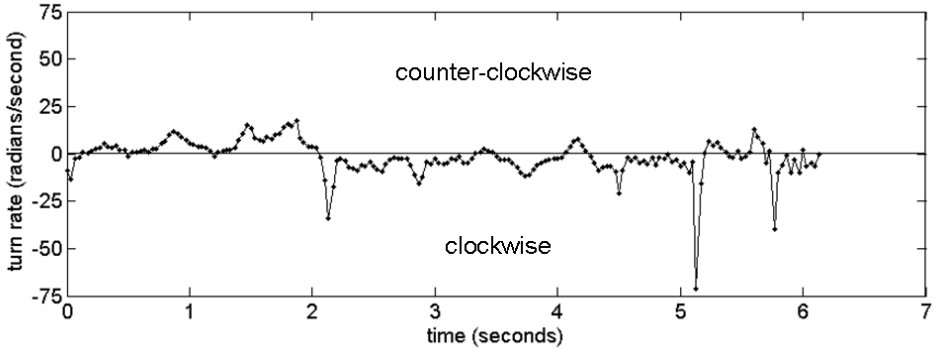


Rutkowski, Quinn, and Willis
J Comp Phys A, 2009

3D Analysis







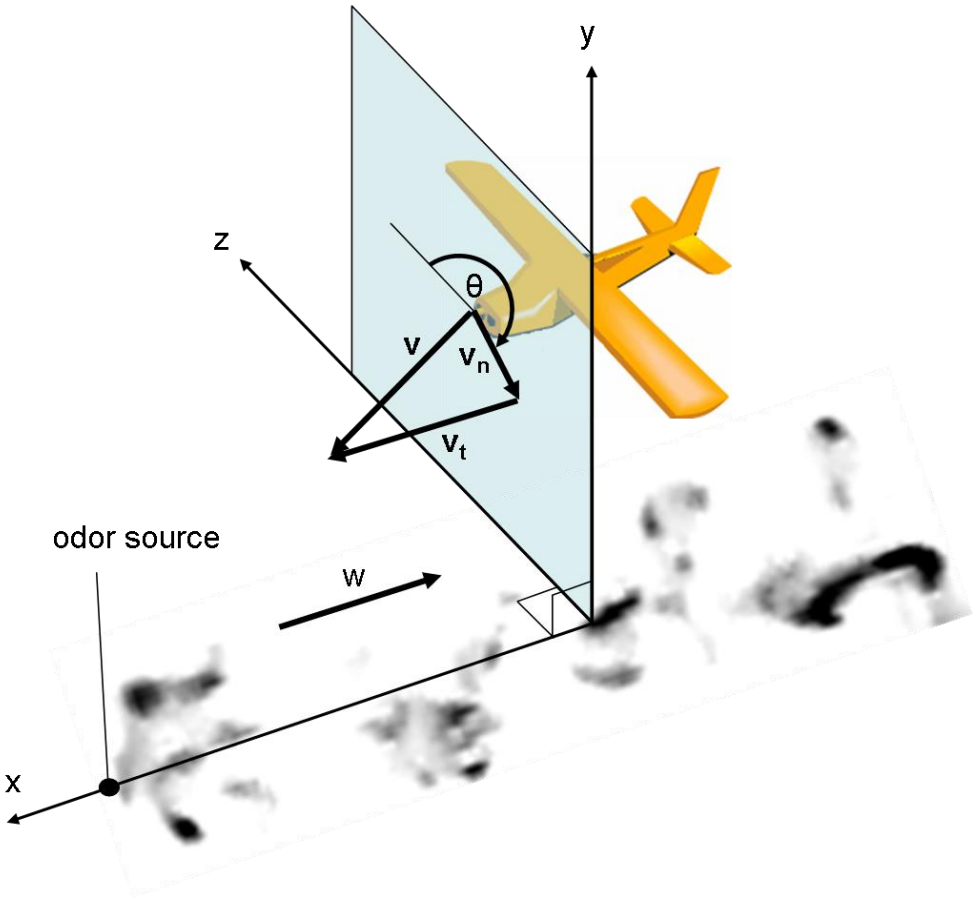
- Turns continuously as viewed from downwind
- Turn rate varies
- Turn direction varies

Rutkowski, Quinn, and Willis
J Comp Phys A, 2009

Bio-Inspired Odor Tracking Strategy

Instead of using inter-turn timers to control horizontal and vertical turning behaviors…

- Motion decomposed into normal ($\mathbf{v}_n$) and tangential ($\mathbf{v}_t$) components relative to wind
- Turn rate of $\mathbf{v}_n$ $\psi = d\theta/dt$ depends on odor concentration
- Magnitude of $\mathbf{v}_t$ depends on odor concentration

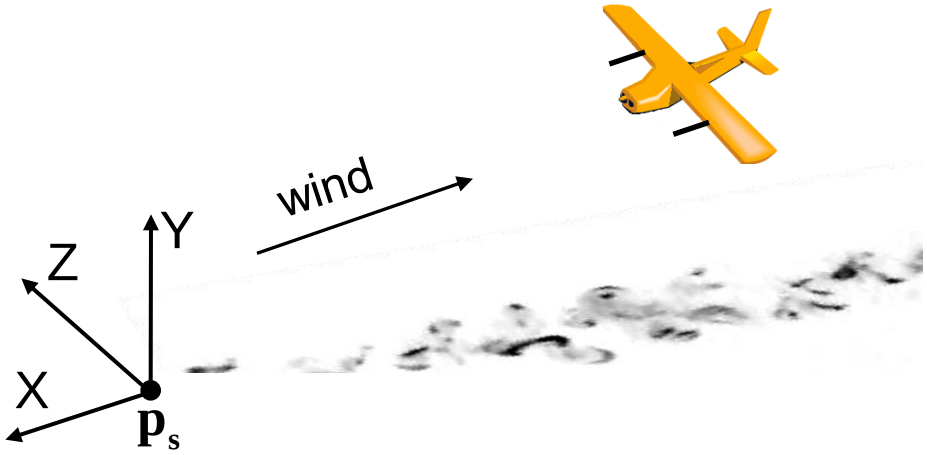


Rutkowski, Quinn, and Willis
ICRA, 2007

Bio-Inspired Odor Tracking Strategy

1. Measure odor concentration

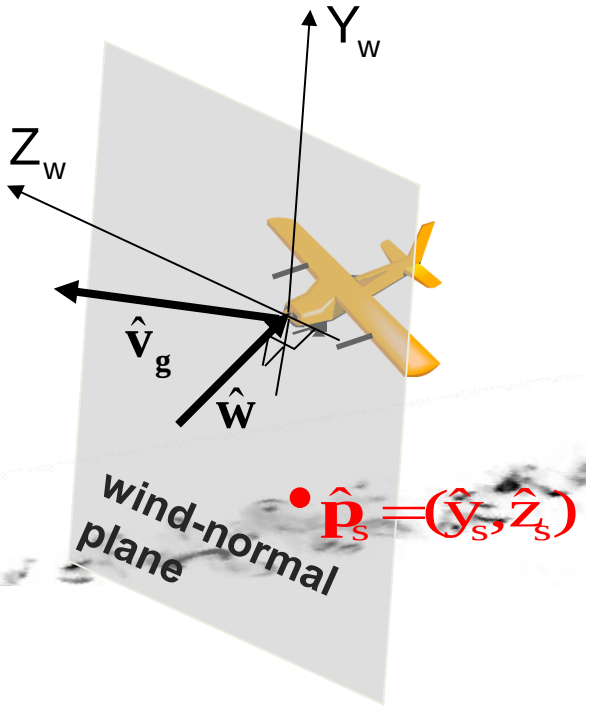
   Two linearly responding odor detectors

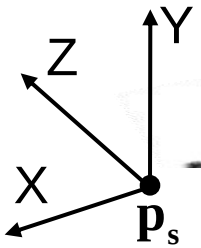


Rutkowski, Quinn, and Willis
ICRA, 2007

Bio-Inspired Odor Tracking Strategy

1. Measure odor concentration
2. Determine wind direction (not trivial)
3. Estimate odor plume centerline
   Average of antenna position (in wind-normal plane) weighted by concentration and a “forgetting factor”





$$\hat{y}_s(t_i) = \frac{\alpha_{decay} C_{sum}(t_{i-1})(\hat{y}_s(t_{i-1}) - \hat{y}(t_i)) + \dots}{C_{sum}(t_i)}$$

$$\hat{z}_s(t_i) = \frac{\alpha_{decay} C_{sum}(t_{i-1})(\hat{z}_s(t_{i-1}) - \hat{z}(t_i)) + \epsilon_{right}(t_i) y_{right}(t_i) + \epsilon_{left}(t_i) y_{left}(t_i)}{C_{sum}(t_i)}$$

$$C_{sum}(t_i) = \alpha_{decay} C_{sum}(t_{i-1}) + \epsilon_{right}(t_i) + \epsilon_{left}(t_i)$$

Rutkowski, Quinn, and Willis
ICRA, 2007

Bio-Inspired Odor Tracking Strategy

1. Measure odor concentration
2. Determine wind direction
3. Estimate odor plume centerline
4. Calculate desired turn rate $\psi=d\theta/dt$

   $c=(c_{right}+c_{left})/2$

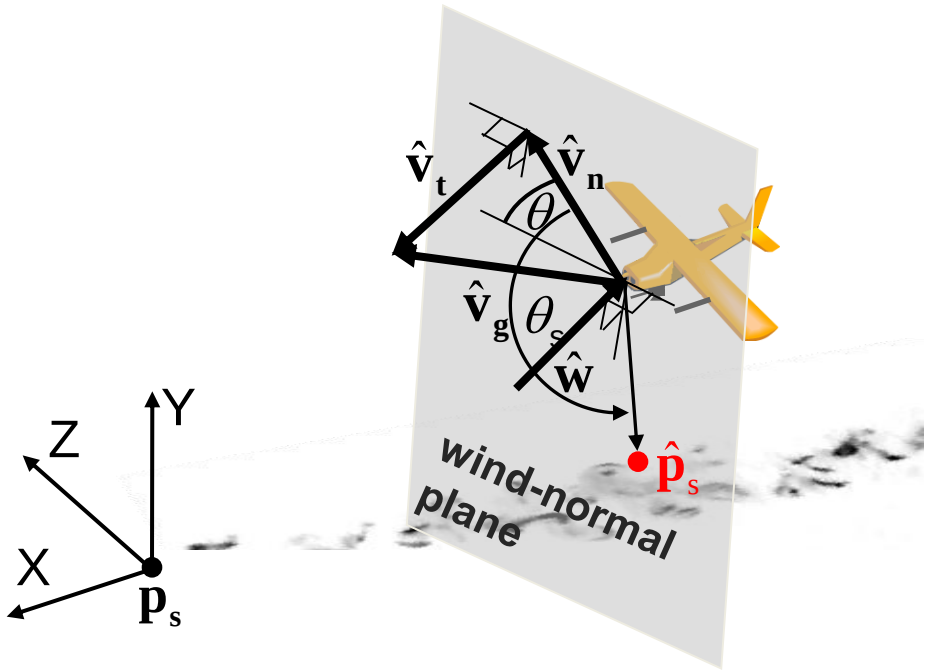
   Turn sharply (6 rad/s) if $c<c_{threshold}$

   Turn as linear function of concentration if $c_{threshold}<c<c_{saturation}$

   Turn softly (1 rad/s) if $c>c_{saturation}$

   Turn toward estimated source location

   $sign(\psi)=sign(\theta_s)$



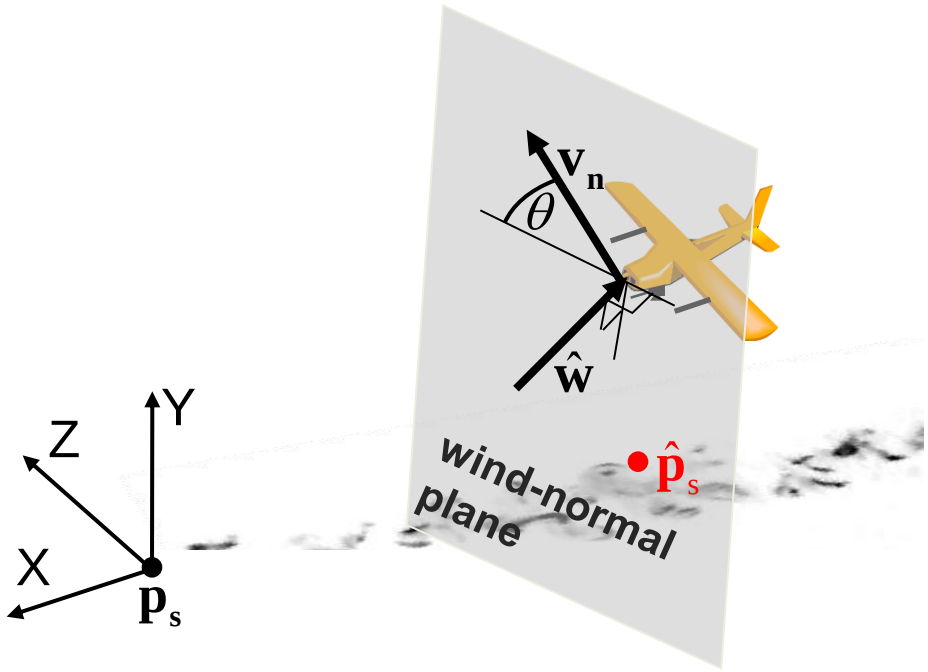
Rutkowski, Quinn, and Willis
ICRA, 2007

Bio-Inspired Odor Tracking Strategy

1. Measure odor concentration
2. Determine wind direction
3. Estimate odor plume centerline
4. Calculate desired turn rate
5. Calculate desired normal velocity

   v_n=30 cm/s

   $\theta = \int \psi \, dt$



Rutkowski, Quinn, and Willis
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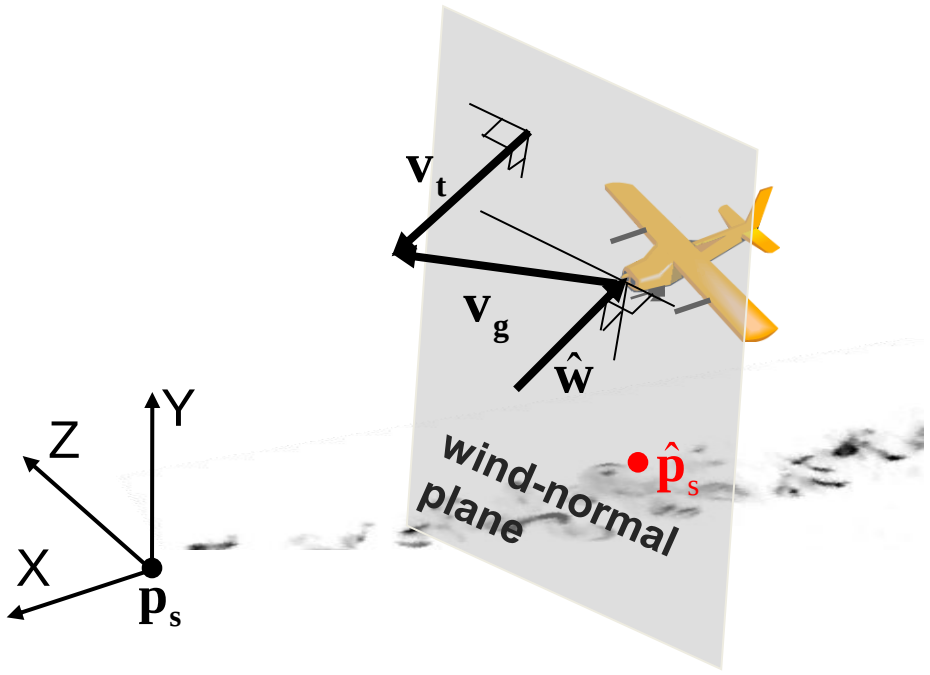
Bio-Inspired Odor Tracking Strategy

1. Measure odor concentration
2. Determine wind direction
3. Estimate odor plume centerline
4. Calculate desired turn rate
5. Calculate desired normal velocity
6. Calculate desired tangential velocity ($\mathbf{v}_t$)

   Surge upwind (30 cm/s) if $c > c_{threshold}$

   Cast slowly downwind (7 cm/s) if $c < c_{threshold}$



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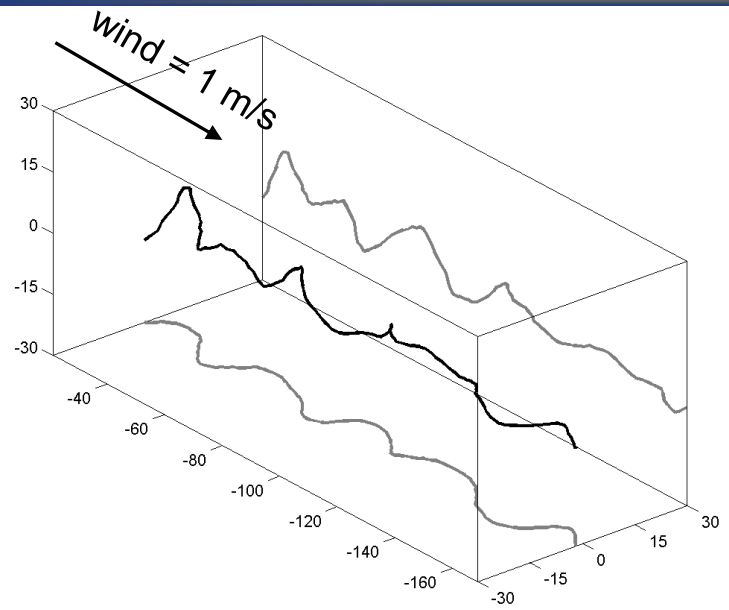
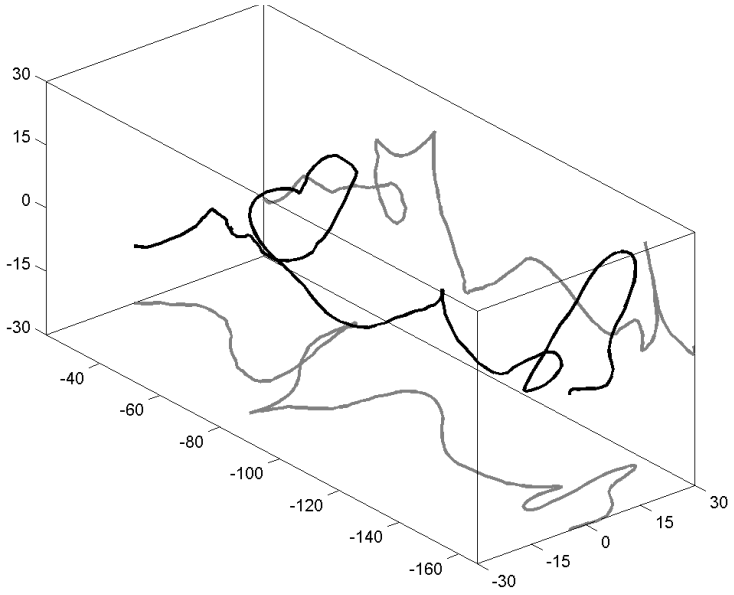
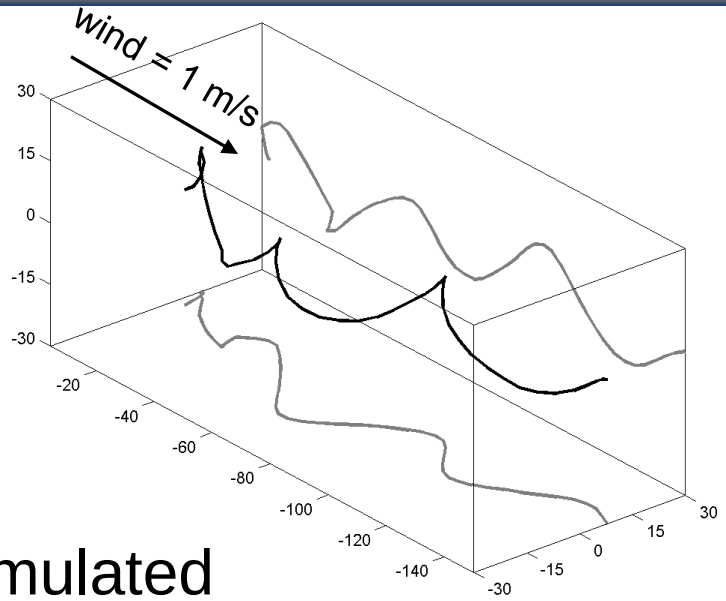
Real vs. Simulated



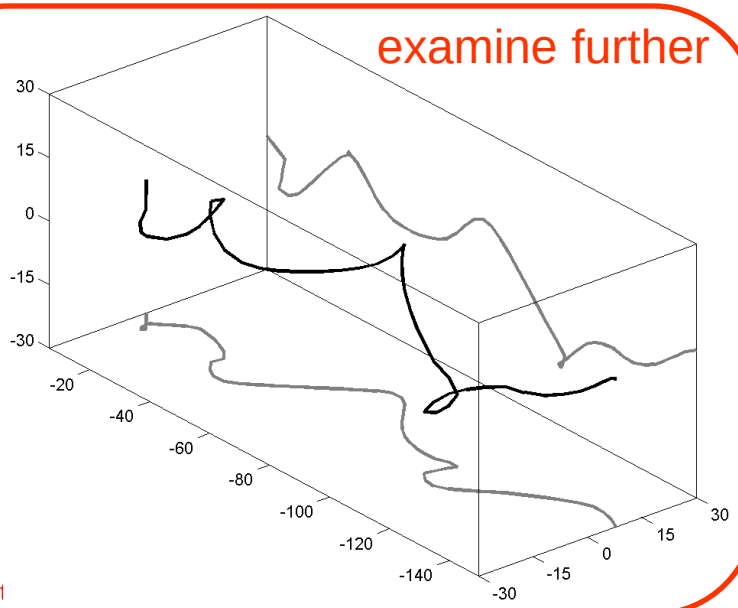
Real





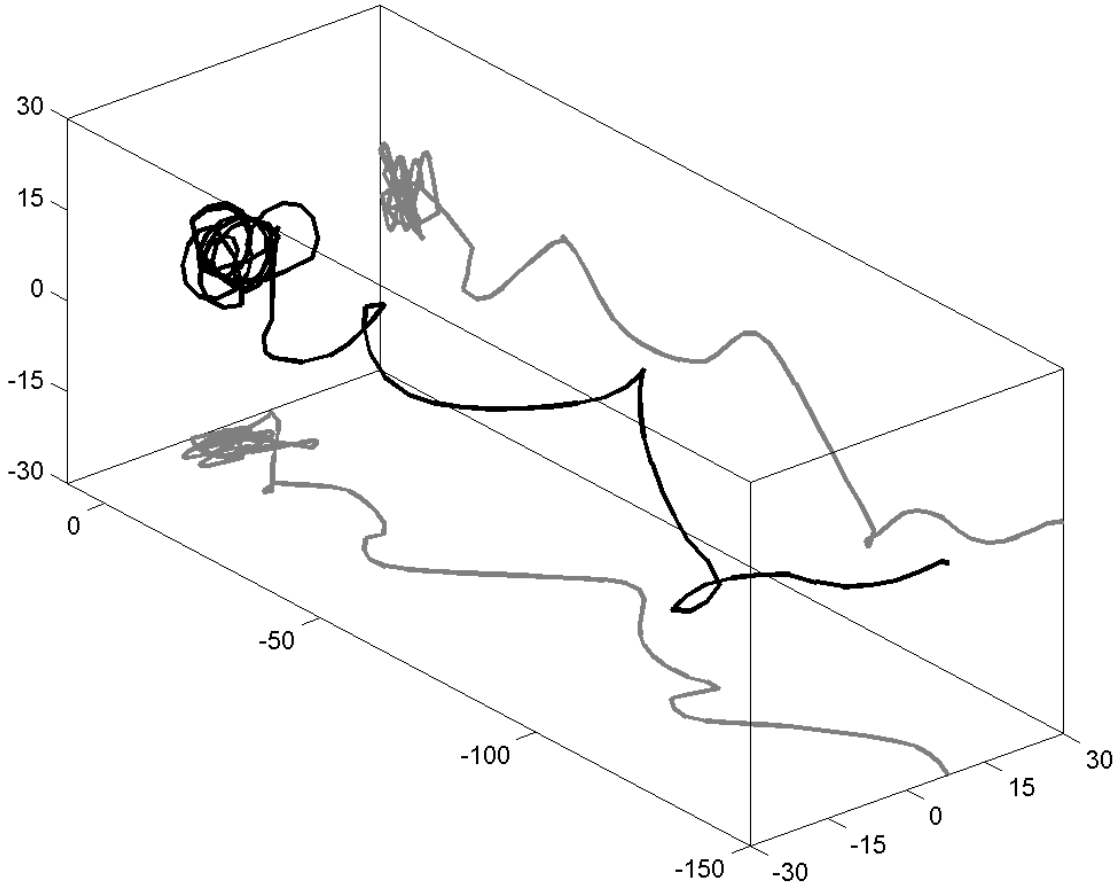
Simulated

examine further



Results

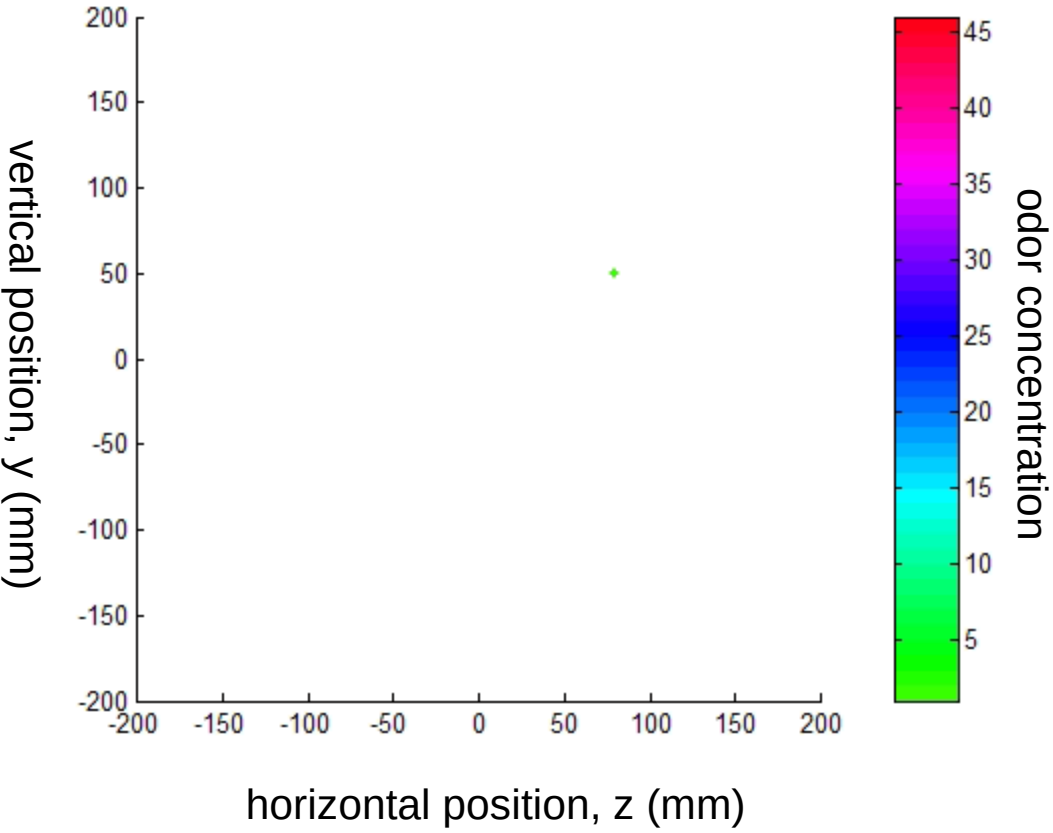
What if odor tracking continues after reaching source?

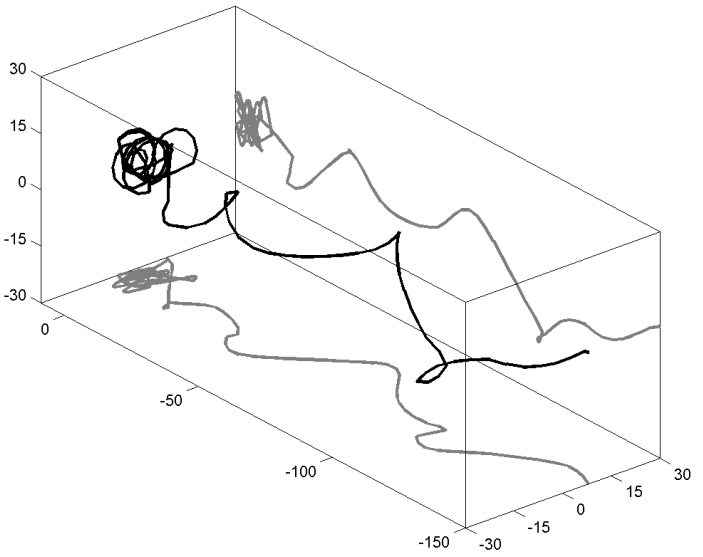


Tracker remains in vicinity of source!

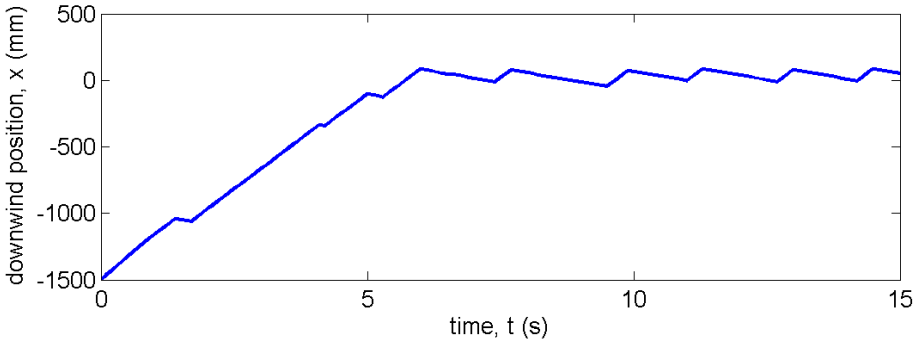
Results

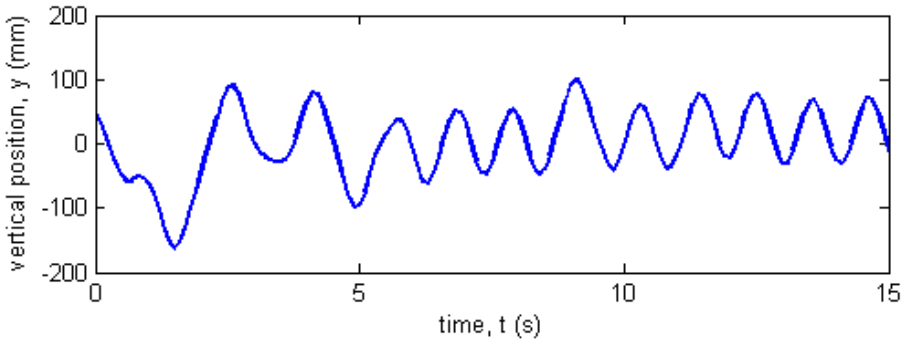
colored dots – tracker position
big black dot - estimated plume centerline

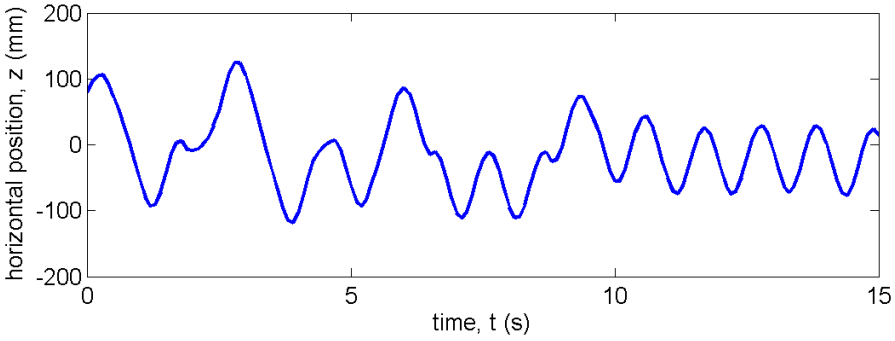


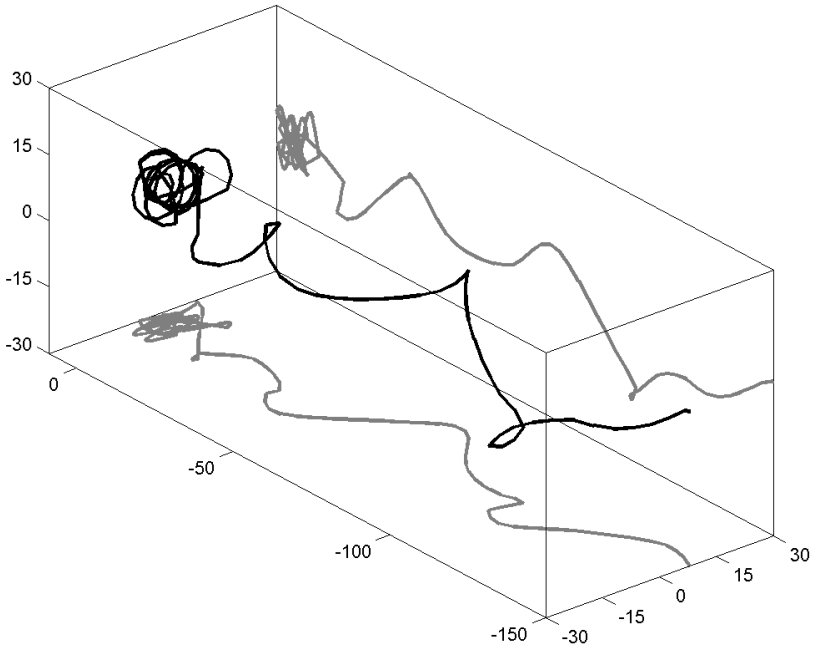


Results









casting and surging

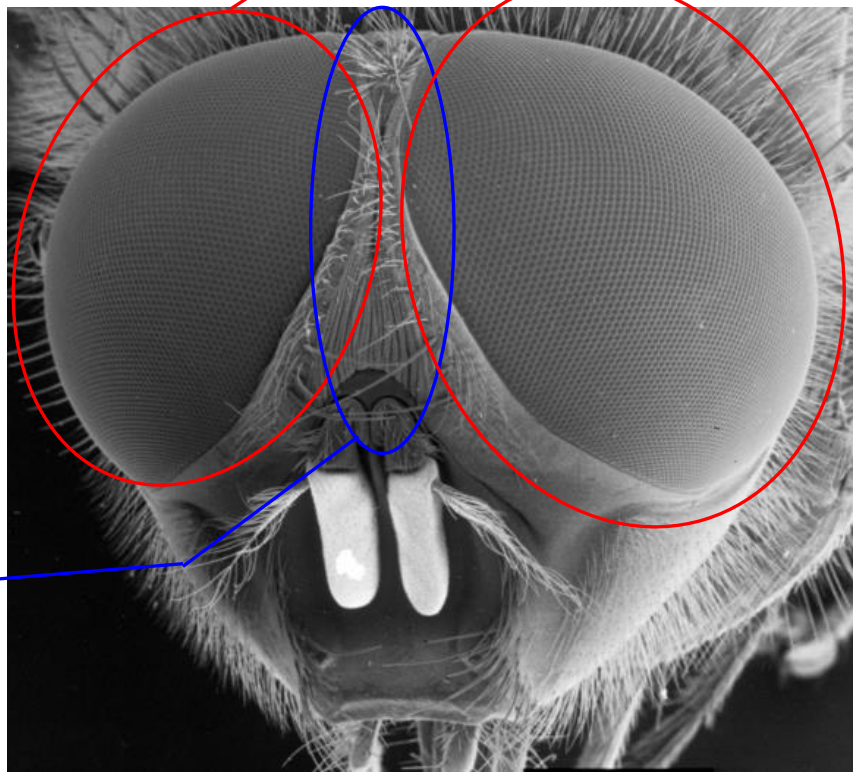
counter-turns without inter-turn timer

“ambiguous” turns

That’s great, but how are wind velocity and self-motion velocity estimated?

Insect Navigation System

- no GPS
- no dedicated accelerometer
- eyes
  - not distance estimators
    - too close together
    - fixed focus
    - small region of overlap
  - optic flow
- head hairs and antennae
  - speed **and direction** of air-current



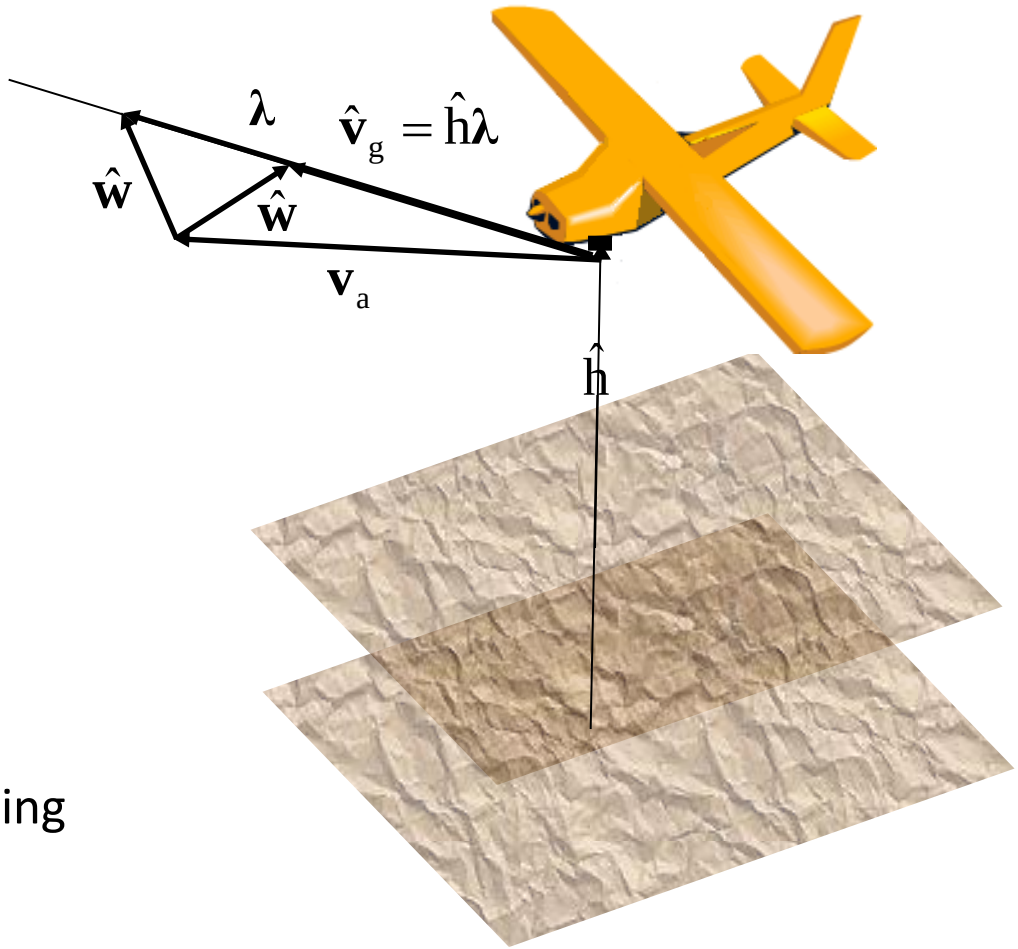
Egomotion and Wind Velocity Estimation

unique values for
- height (h)
- groundspeed ($\mathbf{v}_g$)
- wind velocity ($\mathbf{w}$)

cannot be determined from single measurements of
- air-current velocity ($\mathbf{v}_a$)
- optical flow ($\boldsymbol{\lambda}$)

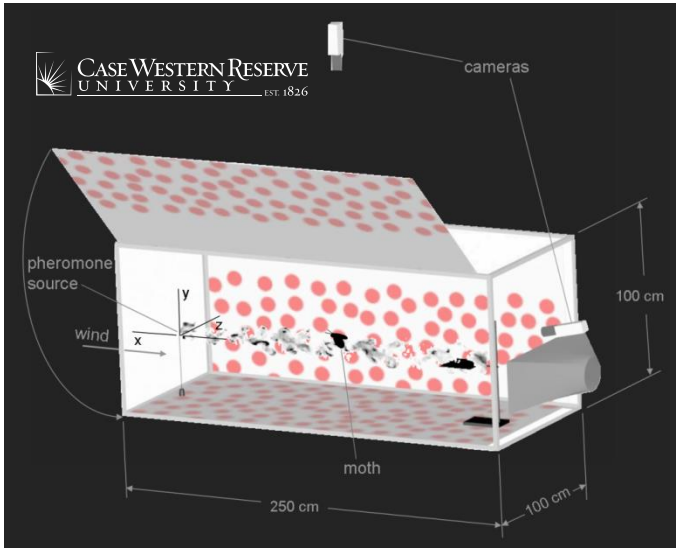
However…

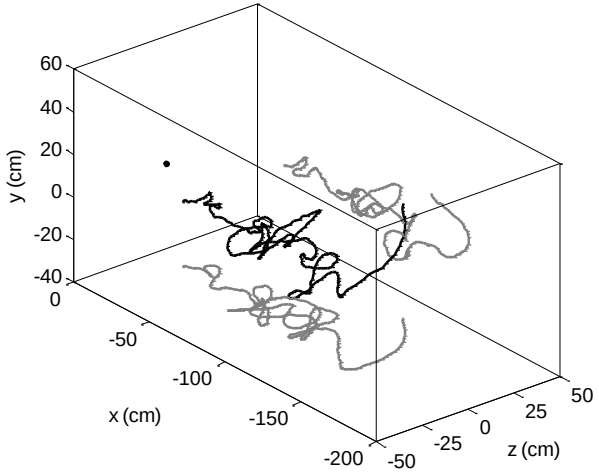
height **can** be estimated by assuming wind is smooth over short time period (~1 s)



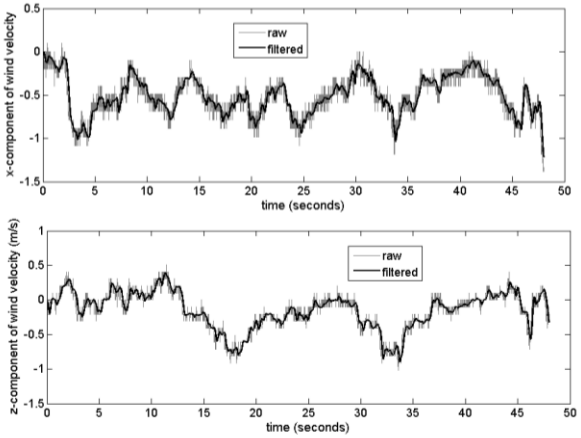
Egomotion and Wind Velocity Estimation

Moth flight track recorded at 30 Hz



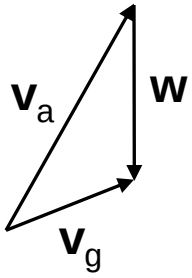


Wind data from open field recorded at 30 Hz



Simulated airspeed data : $\mathbf{v}_a = (\mathbf{v}_g - \mathbf{w}) + \eta_a$

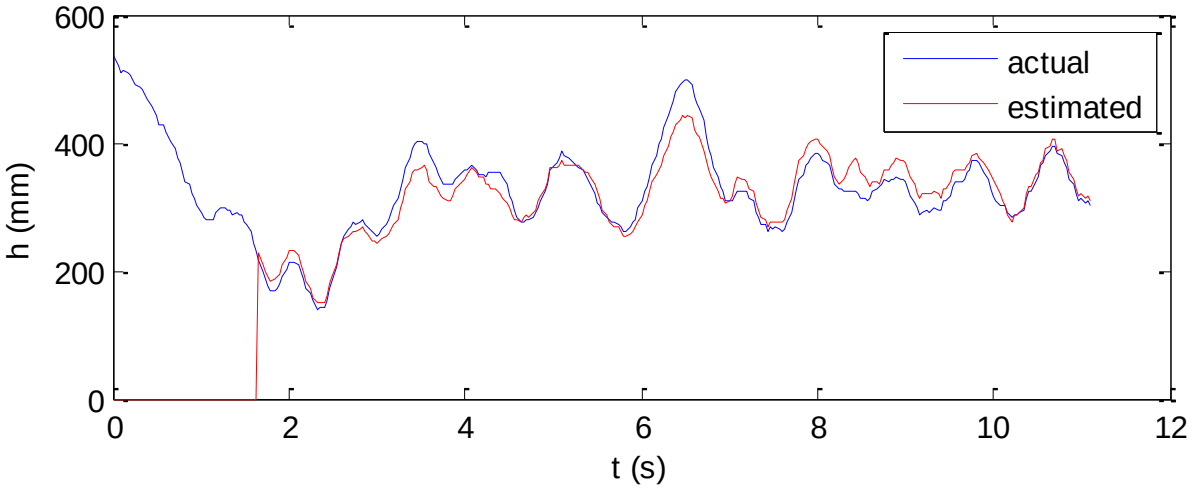
Simulated optical flow data : $\boldsymbol{\lambda} = (\mathbf{v}_g / h) + \eta_{\lambda}$



simulated sensor noise

optical flow: 30 Hz, σ=0.2 rad/s
airspeed: 30 Hz, σ=100 mm/s

Height Estimation Results Using Aero/Optical Fusion



m=2, n=50

$$e_h = \hat{h} - h$$

$$mean(e_h) = -0.12mm$$

$$stdev(e_h) = 22mm$$

Quality of velocity estimation depends on quality of height estimation

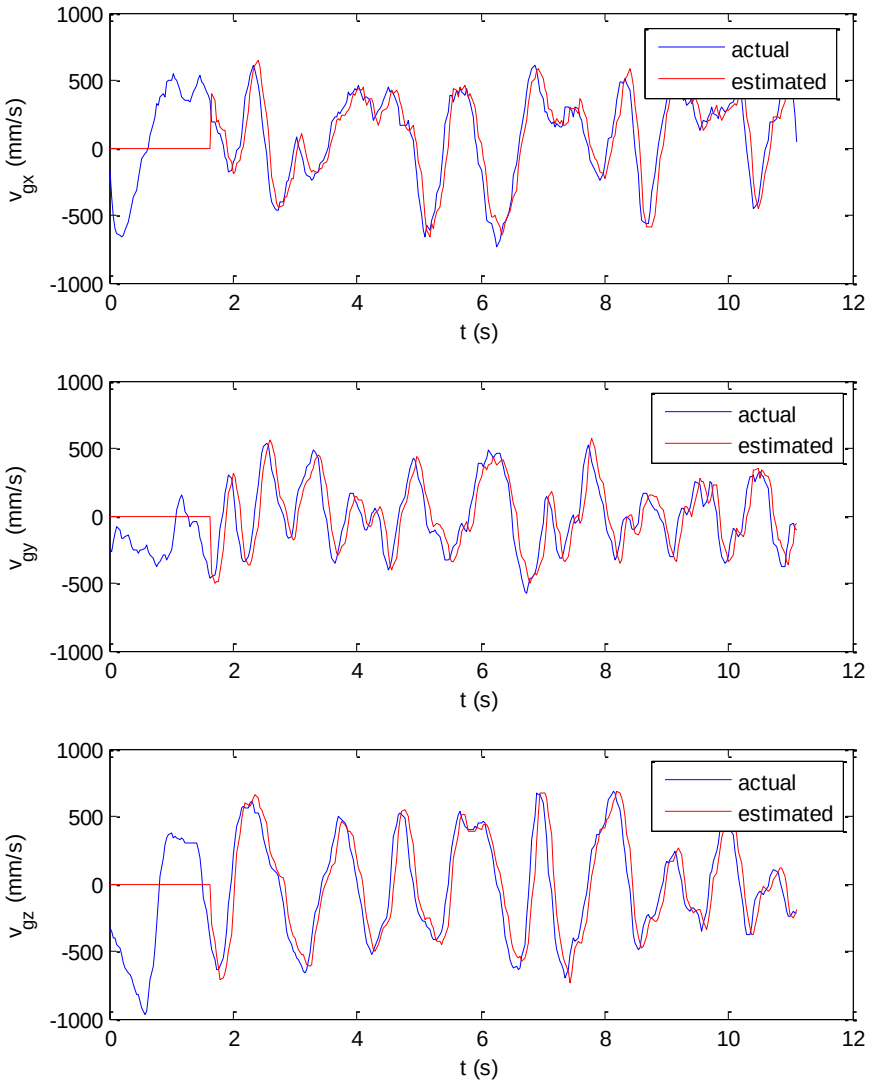
Ground speed Estimation Results Using Aero/Optical Fusion

Ground speed ($\mathbf{v}_g$) estimate lags by two timesteps

Lag caused by finite difference approximation of velocity from optical flow

	v_{gx} (mm/s)	v_{gy} (mm/s)	v_{gz} (mm/s)
$\mathrm{ra}(\mathbf{v}_g(t) - \mathbf{v}_g(t))$			
$\mathrm{ra}(\mathbf{v}_g(t) - \mathbf{v}_g(t_2))$	11	0	5
$\mathrm{sd}(\mathbf{v}_g(t) - \mathbf{v}_g(t))$	10	3	6
$\mathrm{sd}(\mathbf{v}_g(t) - \mathbf{v}_g(t_2))$	140	144	162
	28	27	28

Rutkowski, Miller, Quinn, and Willis
Biol Cybern, 2011



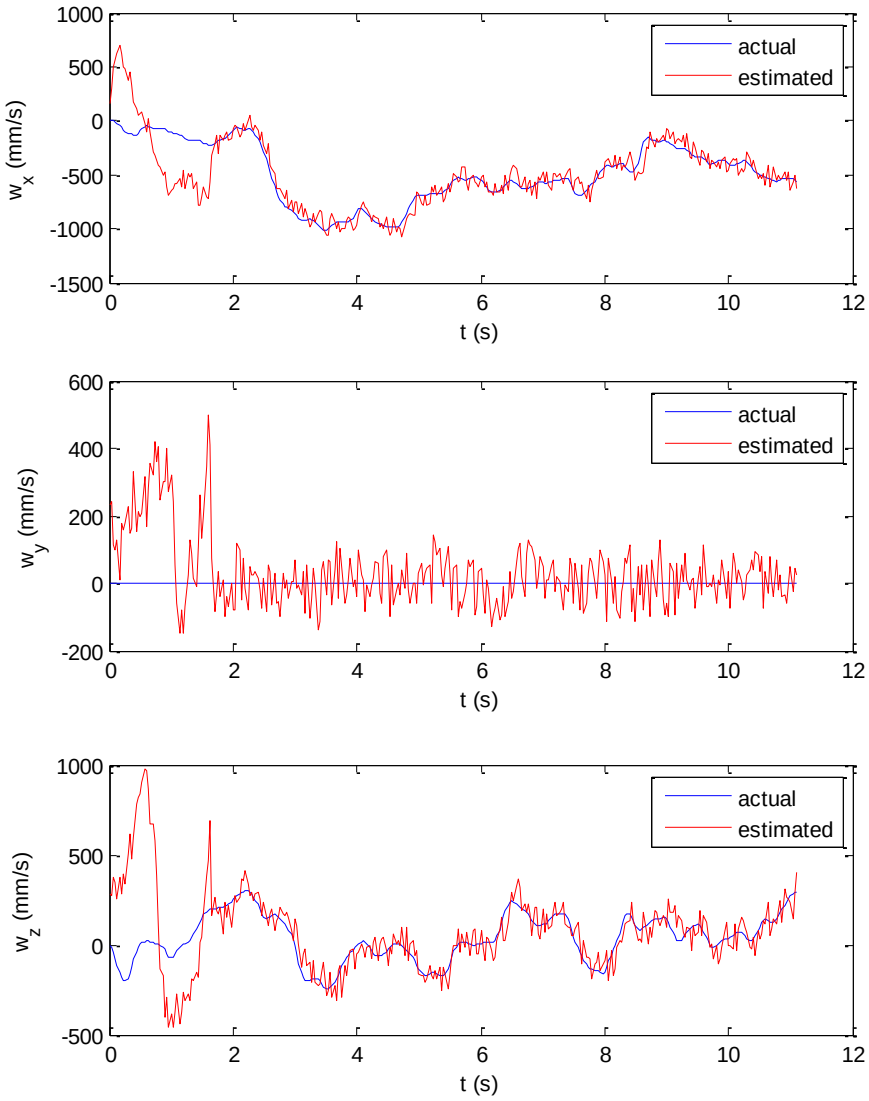
Wind Estimation Results Using Aero/Optical Fusion

Wind estimate also obtained

Lag also present, but minimal compared to noise

	w_x (mm/s)	w_y (mm/s)	w_z (mm/s)
$\mathrm{ran}(v(t)-v(t))$			
$\mathrm{ran}(v(t)-v(t_2))$	12	3	5
$\mathrm{std}(v(t)-v(t))$	10	3	5
$\mathrm{std}(v(t)-v(t_2))$	76	61	68
	64	60	60

Rutkowski, Miller, Quinn, and Willis
Biol Cybern, 2011



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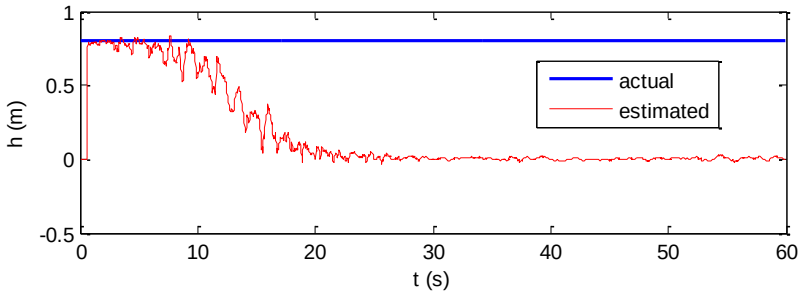
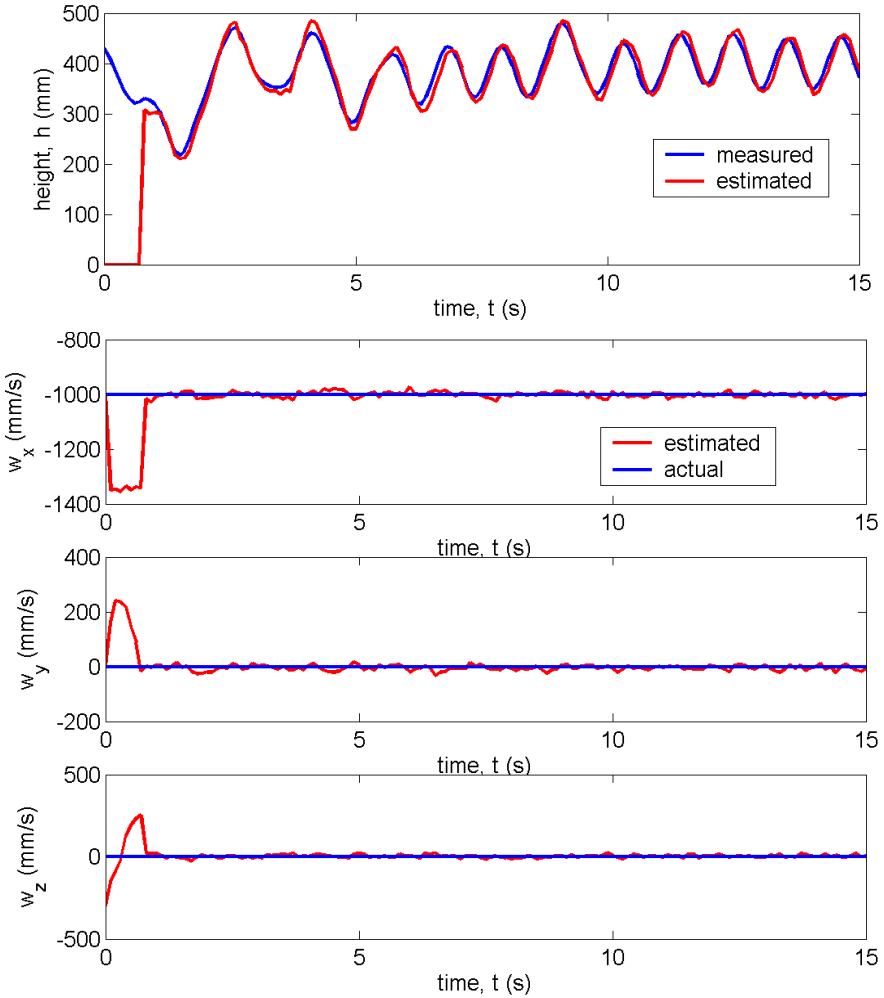
Odor Tracking and Aero/Optical Fusion

- Fusion of vision and airspeed makes odor tracking possible
- Height estimation fails with constant velocity motion



- Motion excitation, as produced by the odor tracking task, allows for state observability



Summary

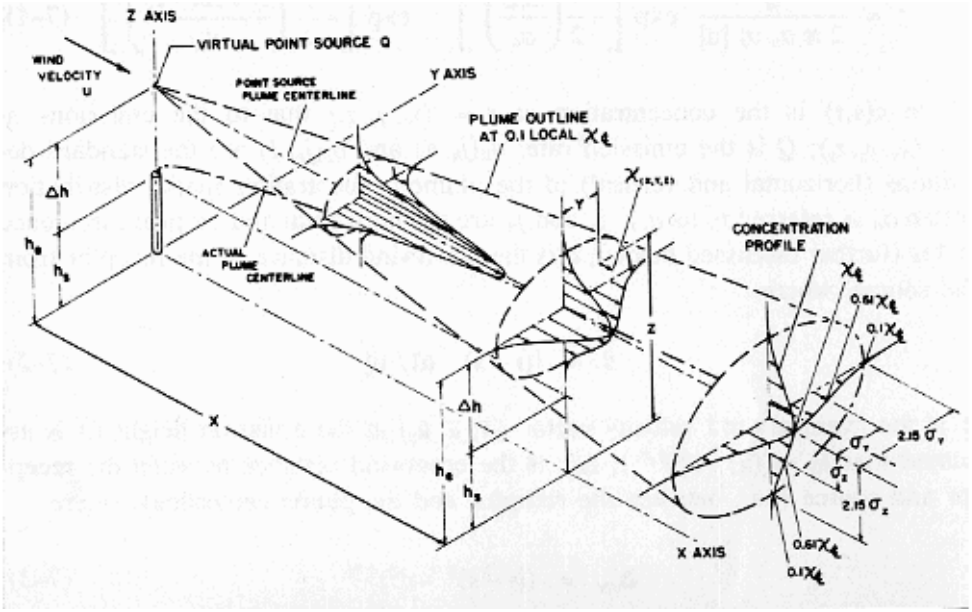
- Moth odor tracking behavior in 3D is NOT a simple extension of 2D ideas
- Moth-like “counter-turning” behavior can be achieved without inter-turn timers
- State and wind estimation can be performed using insect sensory system
- A “drunken stumble” can actually be beneficial

Thank you for your attention!

Additional Slides

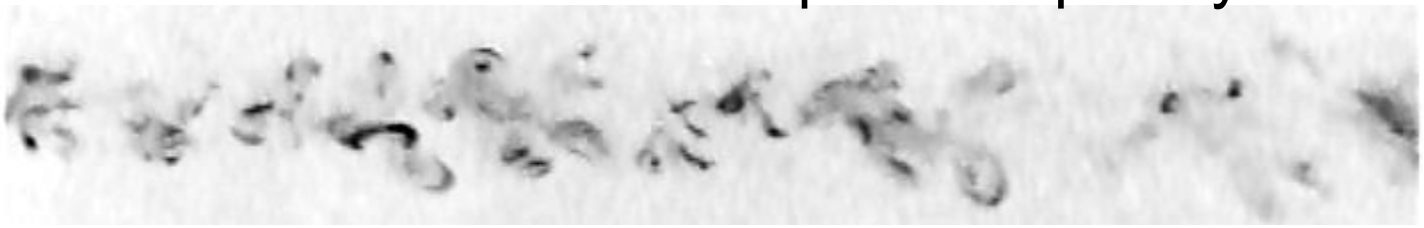
Odor Plume Model

- Normally distributed odor concentration
- Plume narrows with approach to odor source
- Centerline concentration increases with approach to odor source



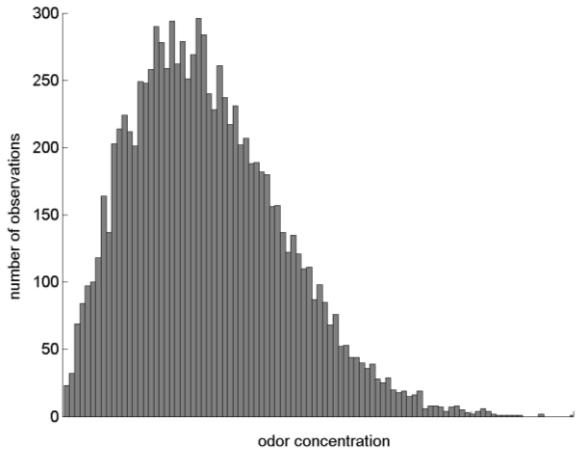
Zannetti

But remember… odor plume is patchy

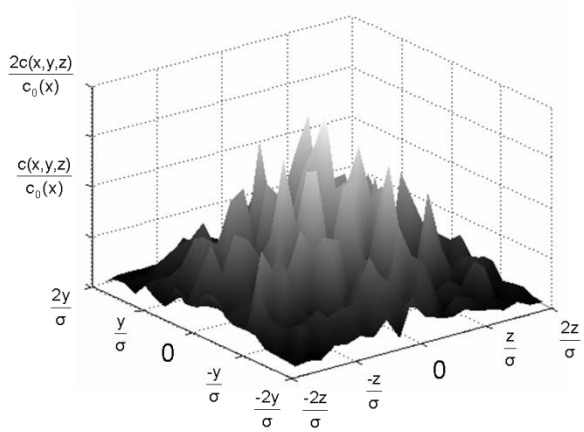


Odor Plume/Sensor Model

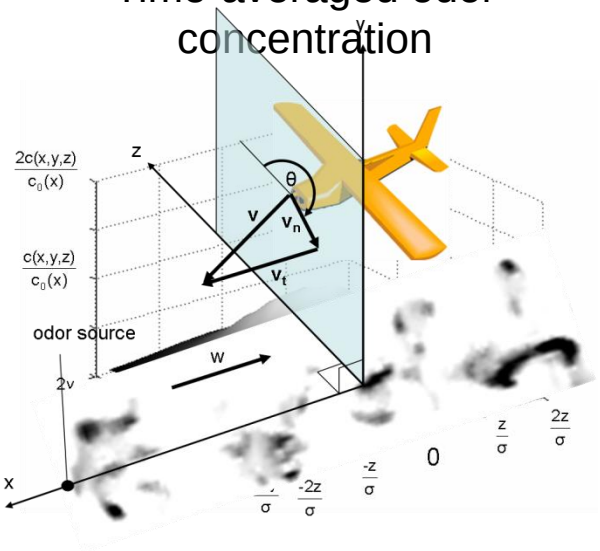
Odor concentration at a single location



Odor concentration at a single timestep

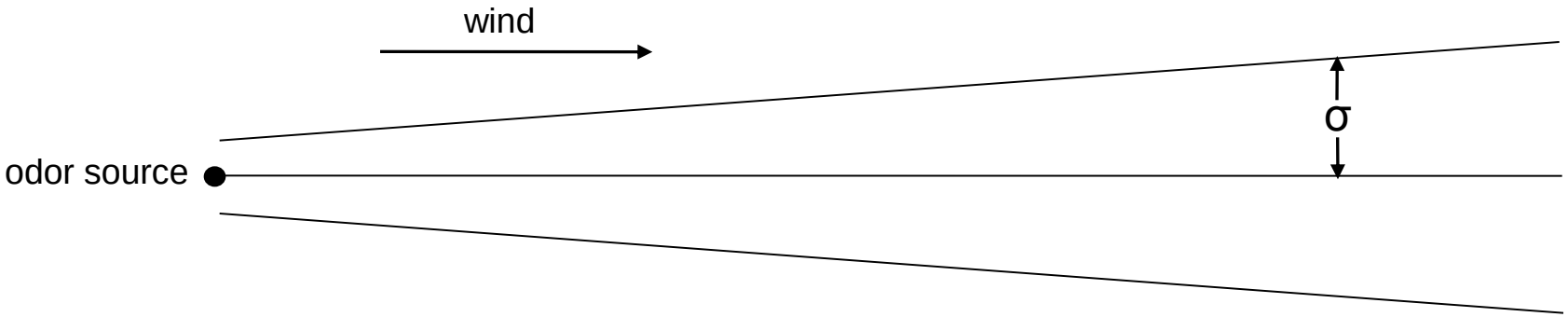


Time-averaged odor concentration



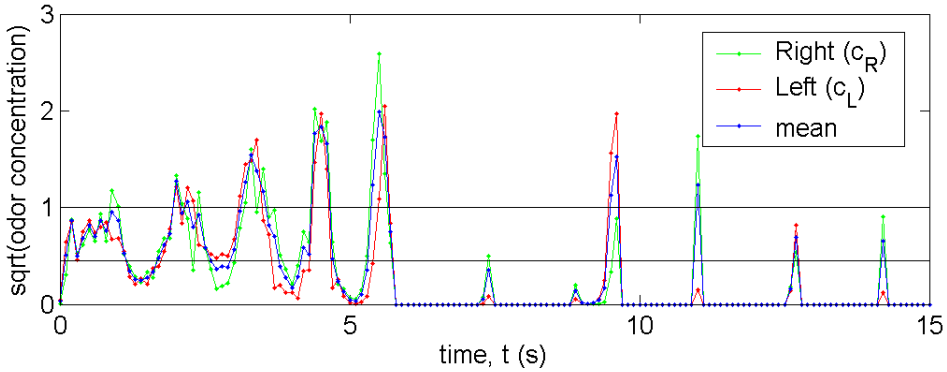
Randomness simulates turbulence

Normally distributed concentration profile



Odor plume narrows with approach to the source

Results

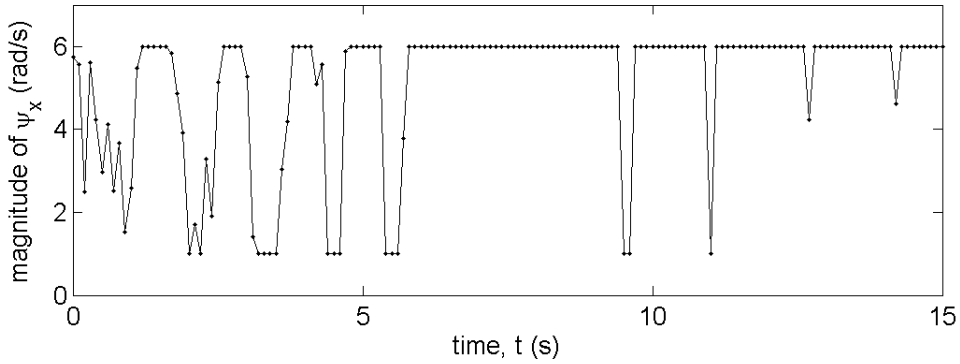


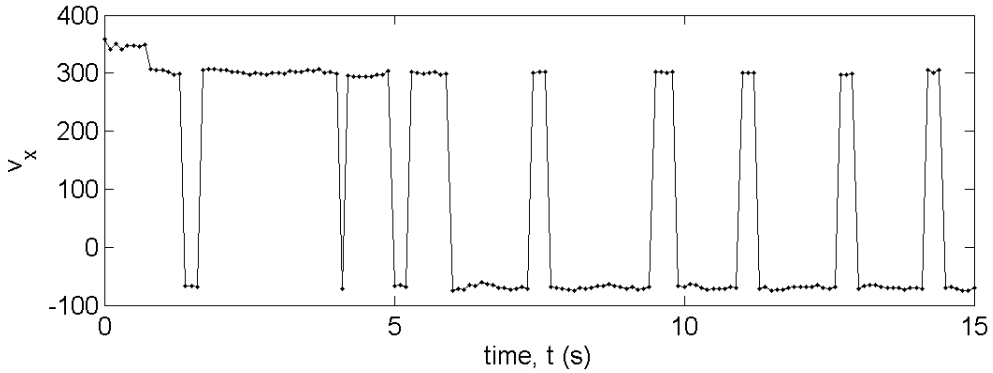
$c_{saturation}$

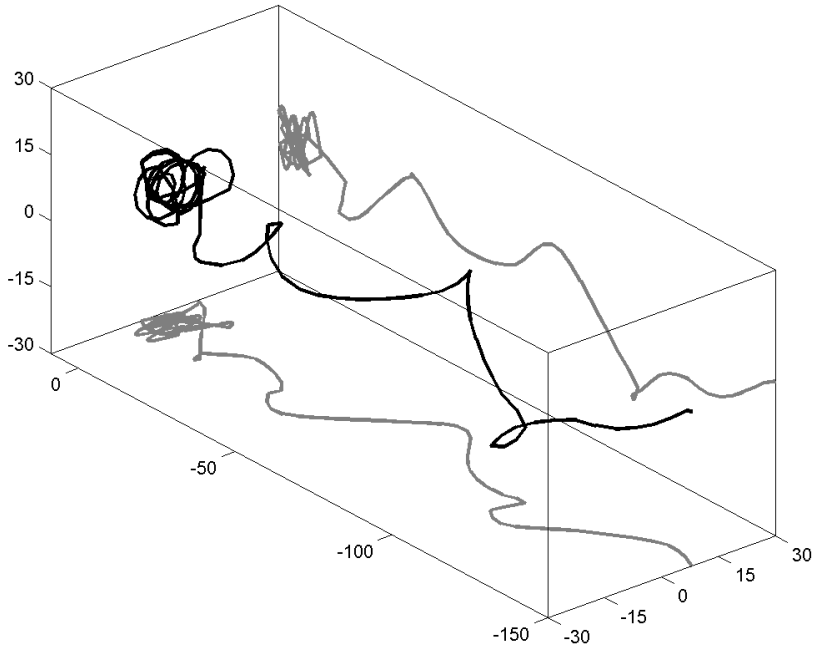
$c_{threshold}$

controls
- upwind velocity
- turn rate

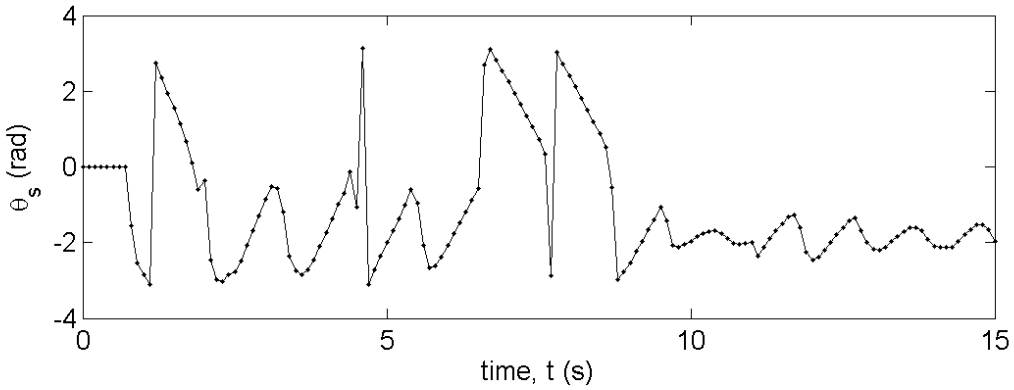
as function of
- odor concentration

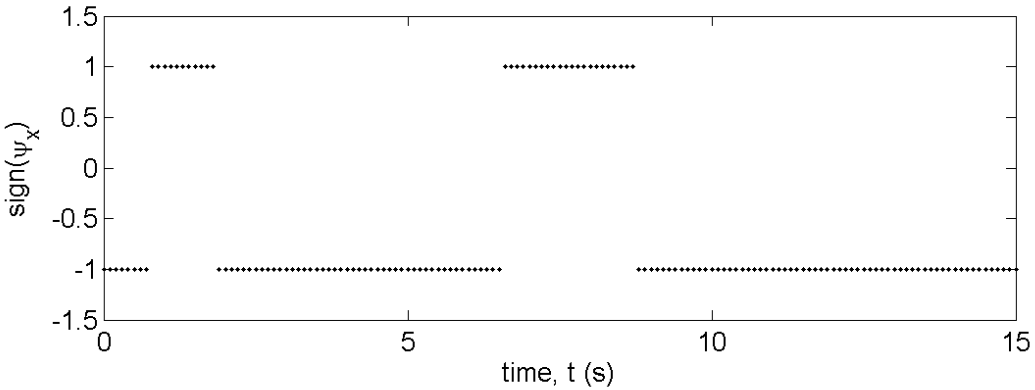


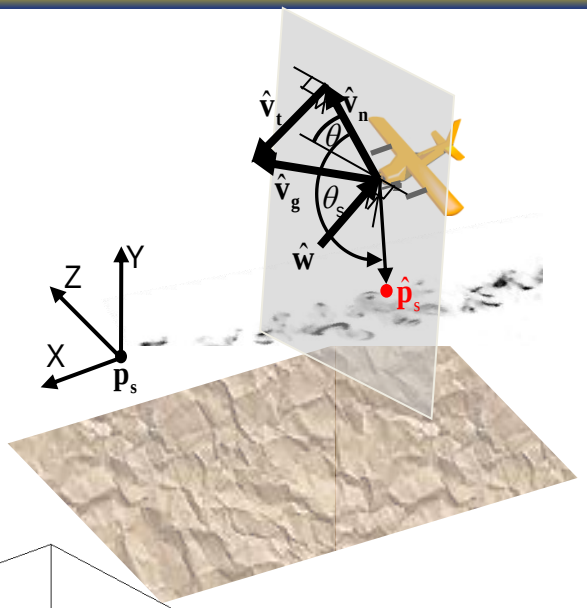


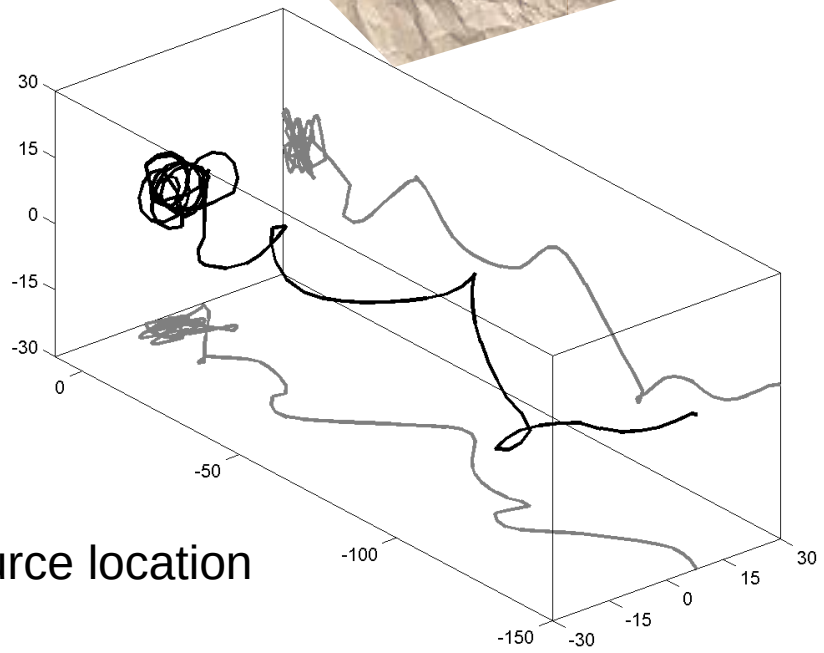


Spiraling Results









Turns in the direction of the estimated odor source location